Using Mathematical Modeling to Identify Causes of Souring During Food Waste Anaerobic Co-Digestion

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May 26, 2022

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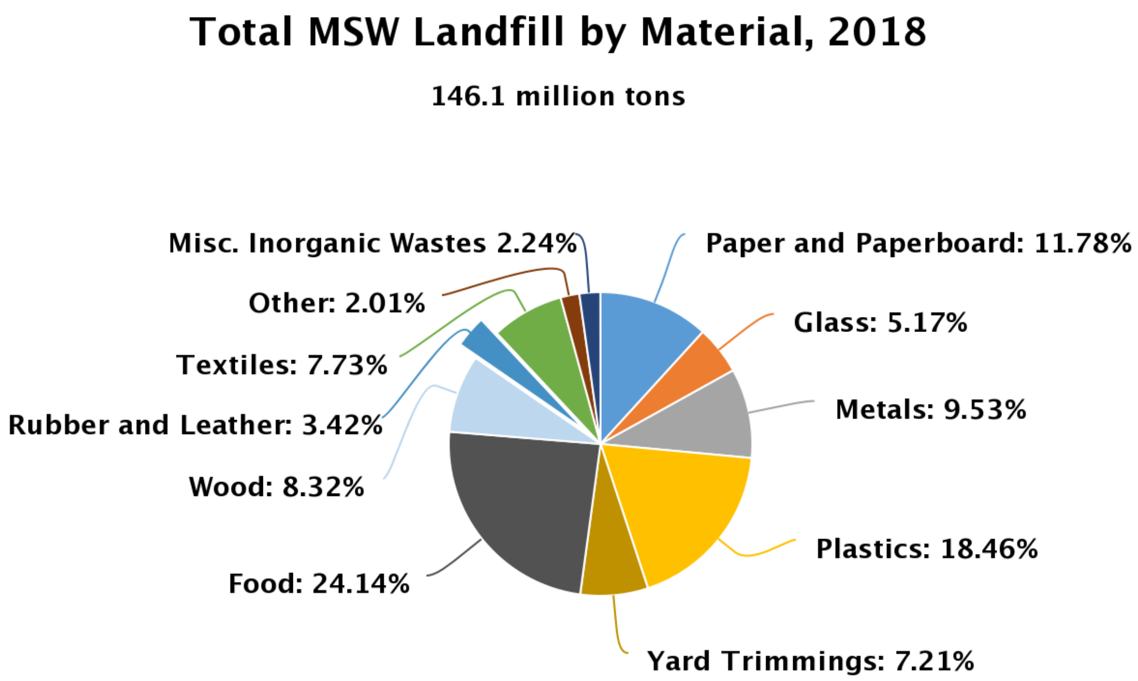


24% of U.S. municipal solid waste is food waste (FW)[1]

[1]U.S. EPA. 2022. National Overview: Facts and Figures on Materials, Wastes and Recycling

6-8% of global greenhouse gas emissions as associated with FW[3]

[3]U.S. EPA. (2018). Advanced Sustainable Materials Fact Sheet. www.nbcnews.com/mach/science/simple-way-we-might-turn-food-waste-green-energy-ncna827166

6 states have banned landfilling of FW[4]

[4]https://www.rts.com/resources/guides/food-waste-America
baltimoresun.com/maryland/baltimore-county/bs-md-co-eastern-sanitary-landfill

~1600 anaerobic digestion facilities in the US[6]

[6]American biogas council, https://americanbiogascouncil.org/biogas-market-snapshot
Picture: www.ennead.com

Only 141 facilities perform FW digestion or co-digestion[7]

[7]US EPA. Anaerobic Digestion Facilities Processing Food Waste in the United States (2017 & 2018)

Why are so few plants performing FW co-digestion?

FW co-digestion start up can be difficult

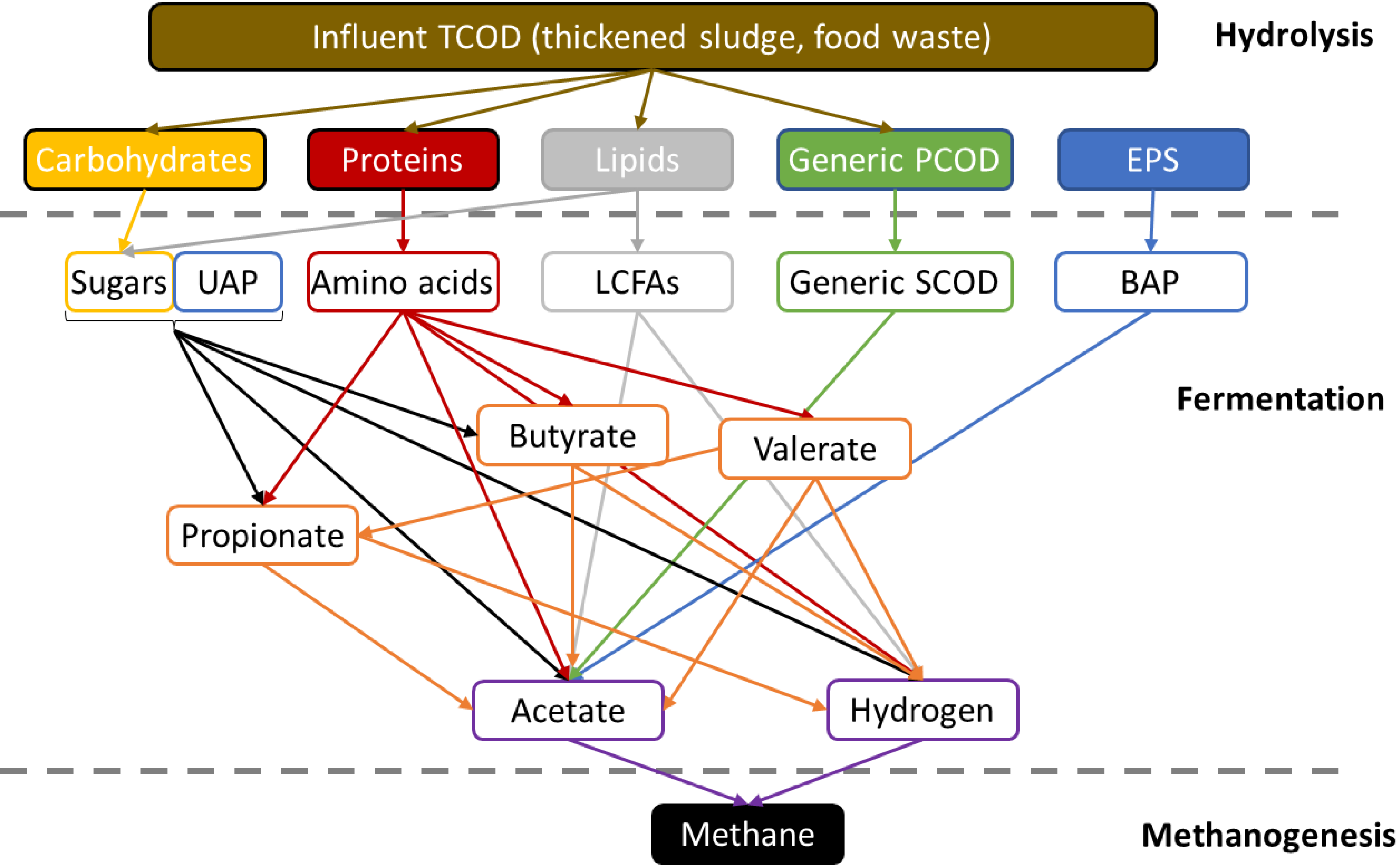
- Food waste feed stream variability[8]
  - Carbohydrates (6-48% DW)
  - Proteins (19-60% DW)
  - Lipids (11-36% DW)
- C/N ratio
  - 20-45 FW[9] vs. 6-12 AD sludge
- Inhibition from volatile fatty acids (VFAs)
- Souring (pH < 6.0)

[8]Morales-Polo et al. (2018). *Appl. Sci.* 8:1804; [9]Chiu & Lo. (2016). *Environ. Sci. Pollut. Res.* 23:24435–24450

Research objective

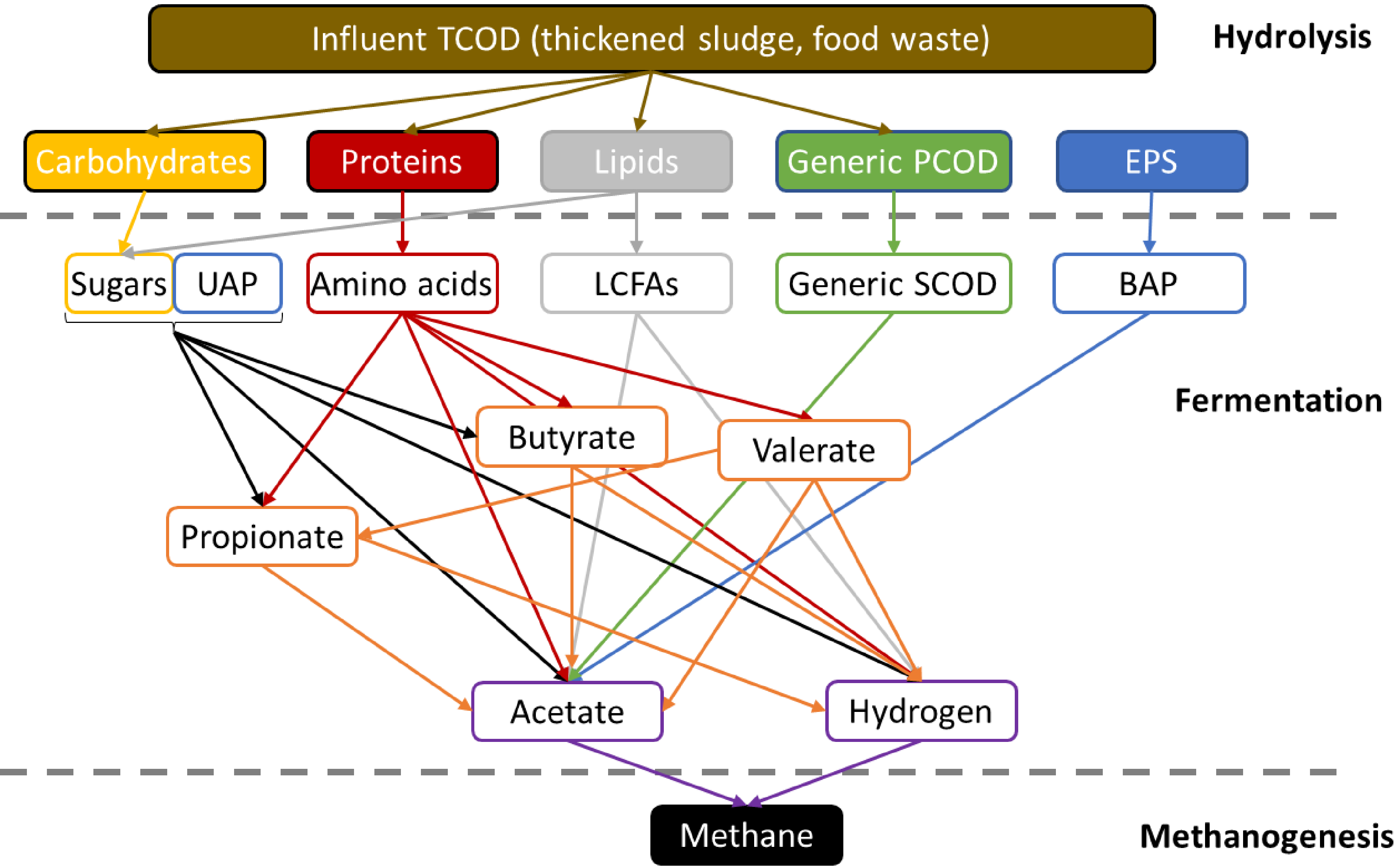
- Developed Food Waste co-Digestion Model (FWcoDM)
  - Anaerobic Digestion Model 1 (ADM1)
  - Combined Activated Sludge-Anaerobic Digestion Model (CASADM)
- Identify the causes and leading indicators of souring
  - Varying organic loading
  - Varying hydraulic retention time (HRT)
  - Feeding frequency

Features of FWcoDM



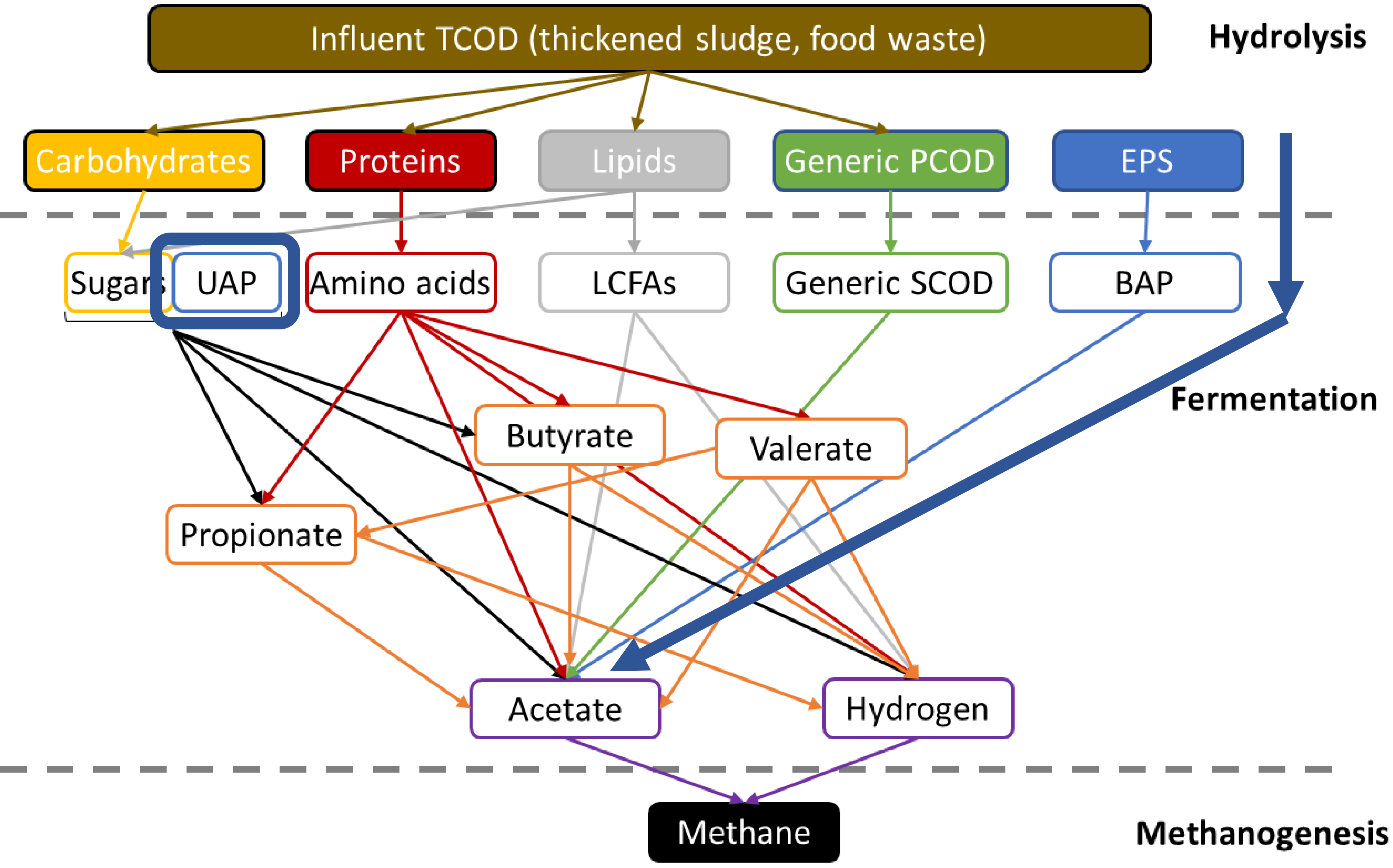
- PCOD=particulate COD (thickened sludge)
- LCFA=long chain fatty acids (palmitate)
- EPS=extracellular polymeric substances
- SMPs=Soluble microbial products (BAP+UAP)
- BAP=biomass associated products
- UAP=utilization associated products

Features of FWcoDM



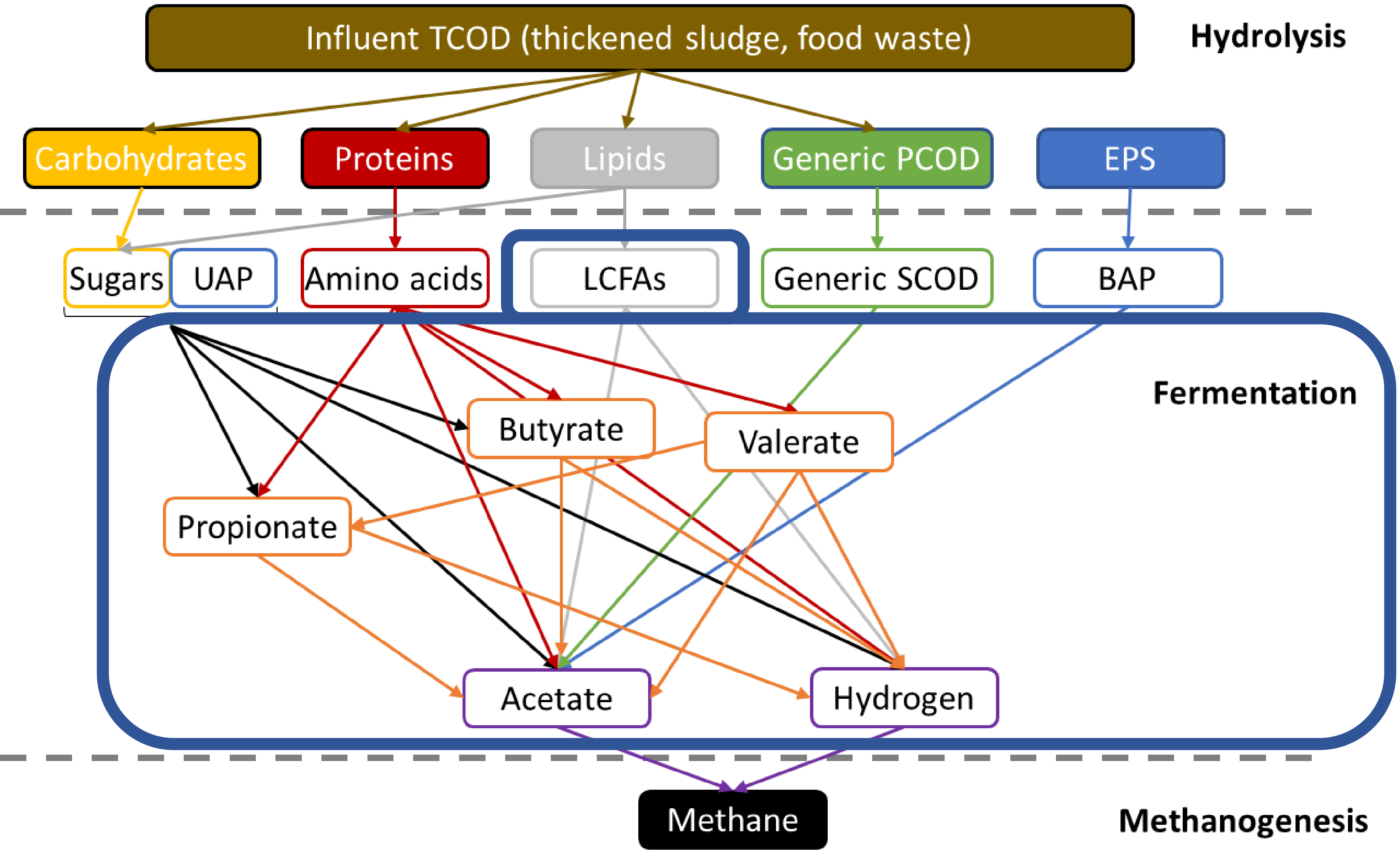
- First order hydrolysis kinetics
- Dual limitation Monod kinetics

Features of FWcoDM



- First order hydrolysis kinetics
- Dual limitation Monod kinetics
- Incorporation of EPS and soluble microbial products (SMPs)

Features of FWcoDM



- First order hydrolysis kinetics
- Dual limitation Monod kinetics
- Incorporation of EPS and soluble microbial products (SMPs)
- Extensive volatile fatty acid (VFA) and LCFA modeling

Inhibition kinetics

- Fermentation

$$I_i = \frac{K_i}{K_i + C_i}$$

  - Chemical i (acetate, H_2, LCFAs)
  - K = inhibition concentration
  - C = chemical concentration

- Methanogenesis

$$I_{pH} = \exp\left[-3\left(\frac{pH - pH_{UL}}{pH_{UL} - pH_{LL}}\right)^2\right], pH < pH_{UL}$$

$$I_{pH} = 1, pH > pH_{UL}$$

  - UL = upper pH limit
  - LL = lower pH limit

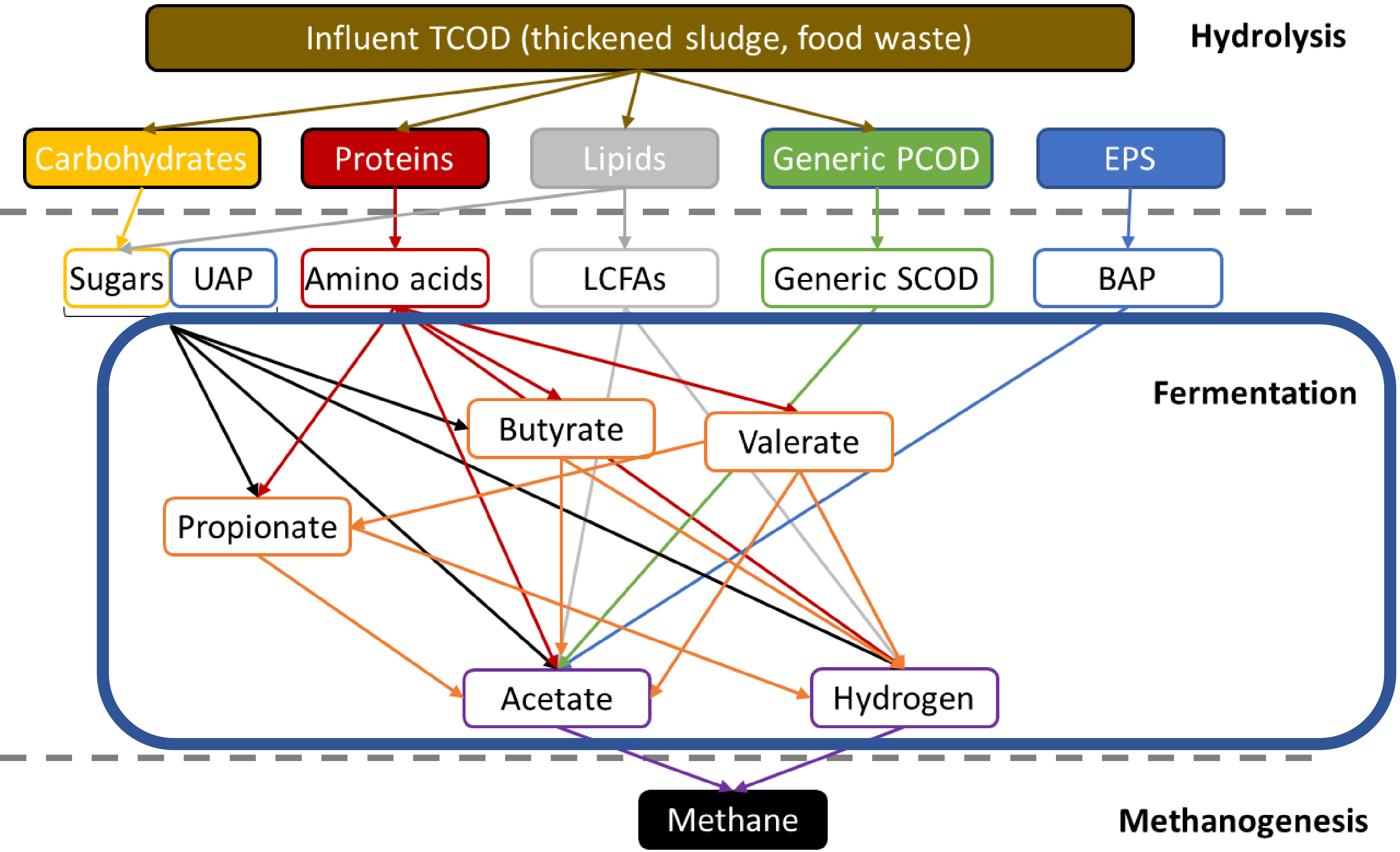
Gas-liquid mass transfer rate

- Mass transfer rate

$$R_i = \frac{V_L}{V_G} K_L a_i \left(C_i^L - C_i^L H_i RT \right)$$

  - Chemical i (CH_4, CO_2, NH_3, H_2)
  - L = liquid, G = gas
  - V = Volume
  - C^L = Liquid phase concentration
  - H = Henry's law constant
  - T = Temperature
  - R = Gas constant
  - K_La = Mass transfer coefficient

Features of FWcoDM

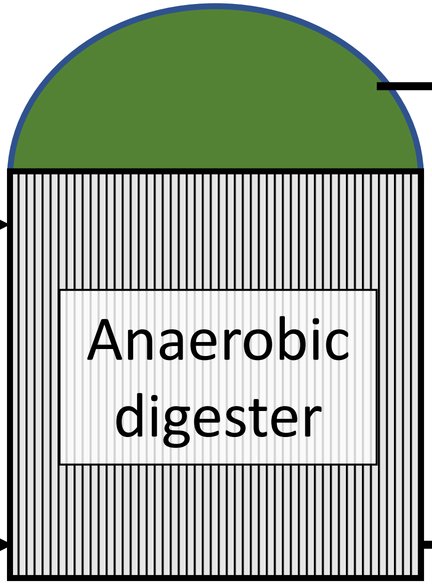


- First order hydrolysis kinetics
- Dual limitation Monod kinetics
- Incorporation of EPS and soluble microbial products (SMPs)
- Extensive fatty acid modeling
- pH and chemical speciation of VFAs, CO_2, and NH_4^+ using proton balances

Model parameters

Food waste
- 200 g TCOD/L
- 31 g VSS/L
  - 41% carbs
  - 32% proteins
  - 27% lipids
- pH 5.2
- Sugar 35 g/L
- Amino acids 35 g/L
- Acetate 295 mg/L
- Propionate 219 mg/L
- Butyrate 44 mg/L
- Valerate 51 mg/L

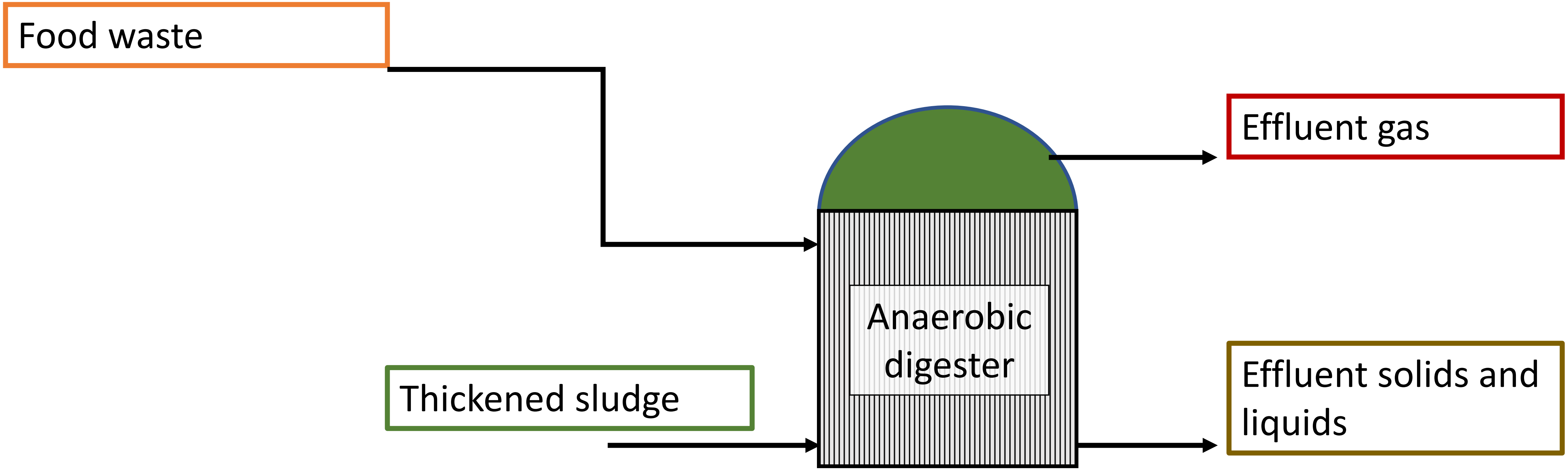
Thickened sludge (ThS)
- 50 g TCOD/L
- 1.5 g SCOD/L
- 34 g VSS/L
  - 23% carbs
  - 8% proteins
  - 55% lipids
  - 14% generic PCOD
- pH 6.55



- Gas composition (CH_4, CO_2)
- Biogas production

- pH
- Sludge reduction
- Soluble COD and VFAs
- NH_4^+
- Bicarbonate alkalinity
- Total alkalinity

Model parameters



$$\mathrm{Vol}\frac{\partial C_h}{\partial t} = \sum_{\substack{\mathrm{ThS}\\ \mathrm{FW}}} Q_{i,in} C_{i,h,in} - \sum_{\mathrm{Effluent}} Q_{i,out} C_{i,h,out} + \mathrm{Vol} \sum R_h \, I_{h,pH}$$

Vol = Reactor volume

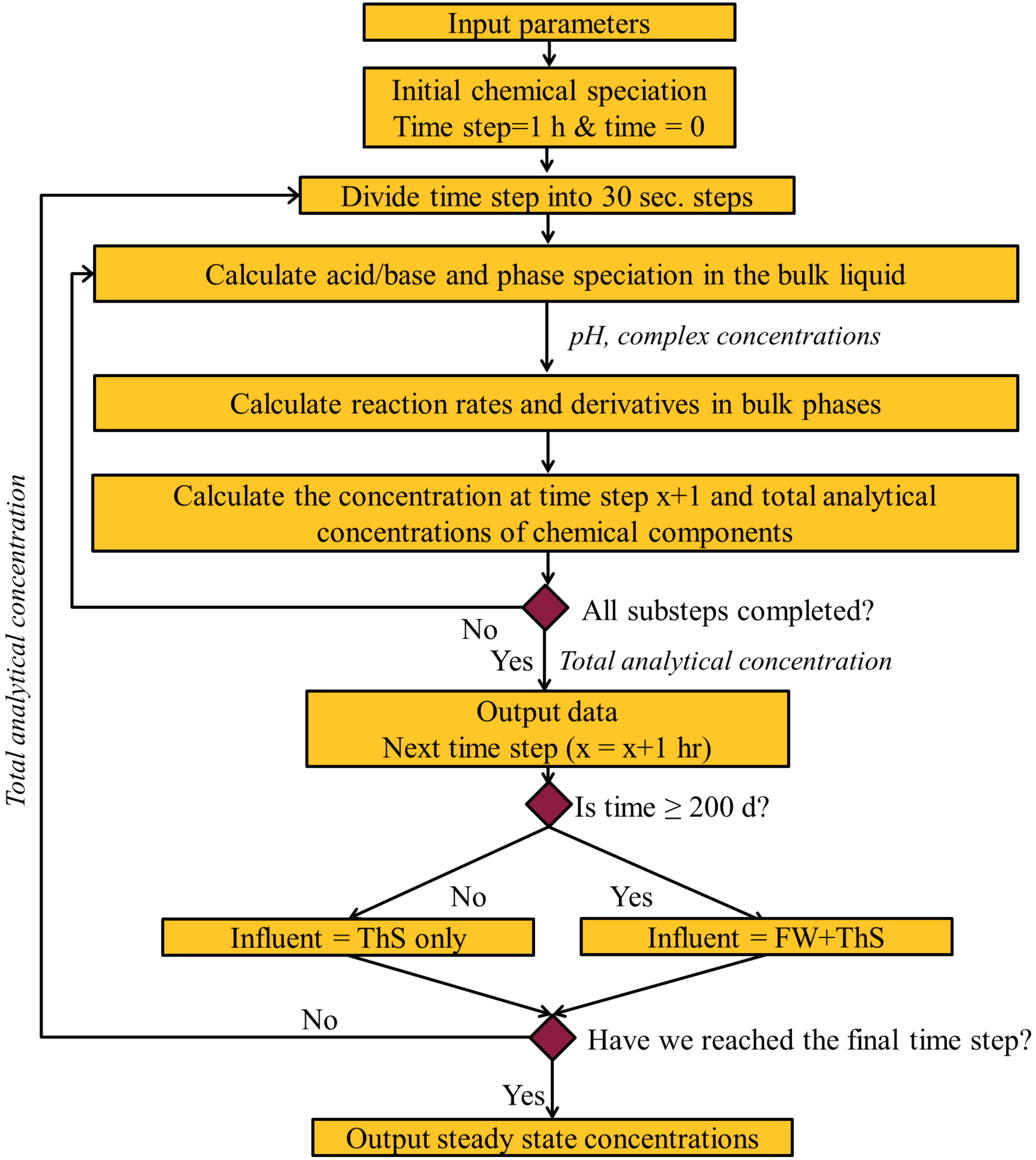
Q = Volumetric flow rate

R = Reaction rate

I = Inhibition rate

Model execution

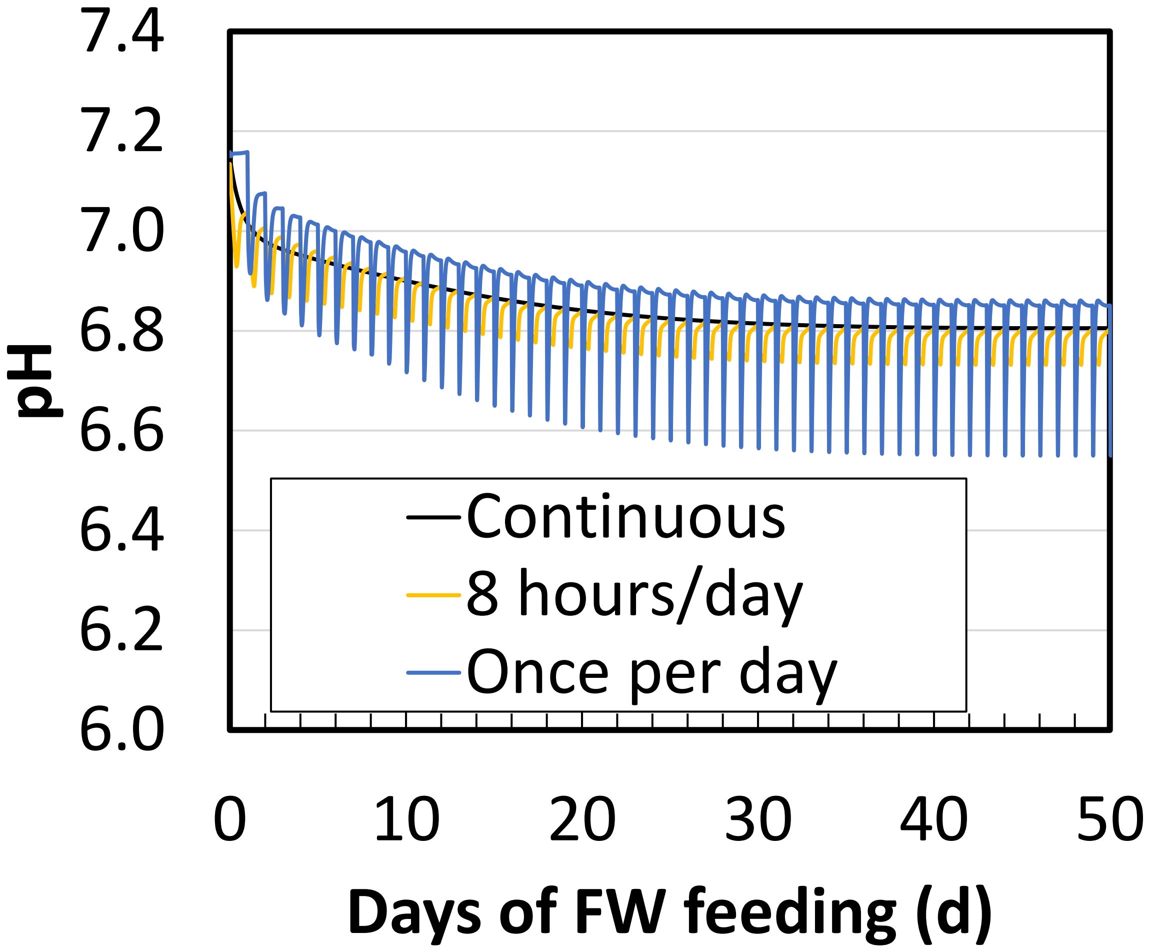
- MATLAB 2021a using ordinary differential equations solver
- Run for 200 d with thickened sludge-only (ThS) as the input
- Run for an additional 200 d with 50% FW+ 50% thickened sludge by volume as input
- < 10^{-5} numerical error
- Souring pH < 6.0
- Total alkalinity = Bicarbonate alkalinity + VFA alkalinity



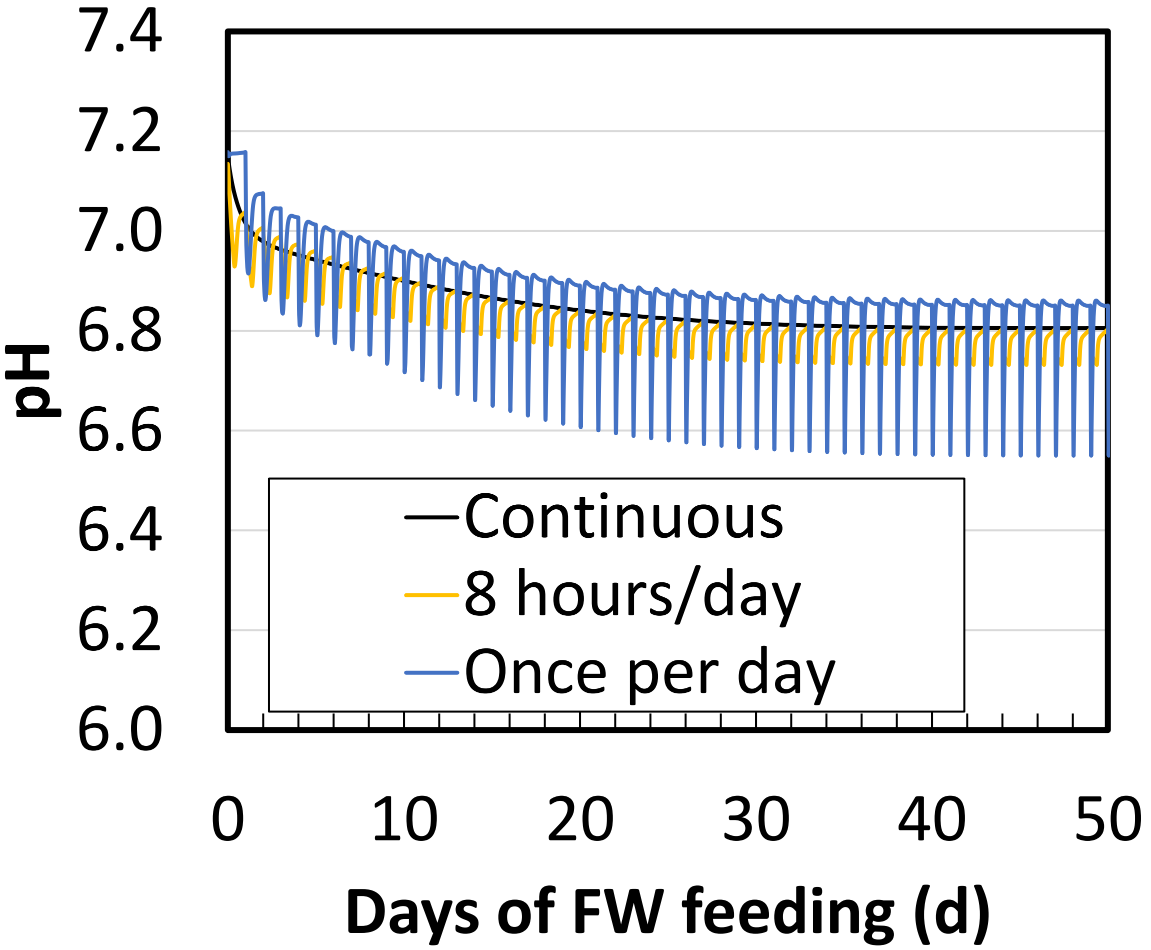
Scenario overview

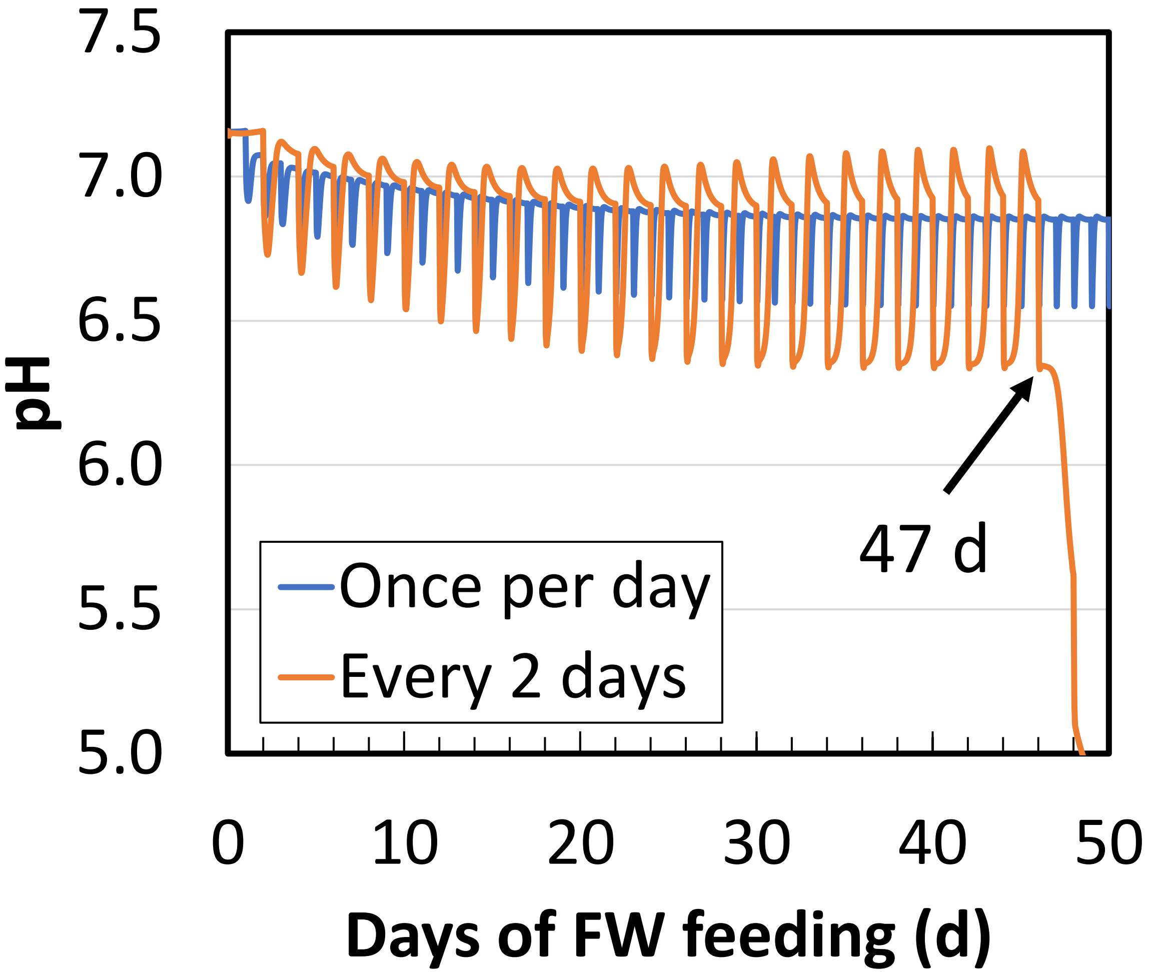
- Identify the causes and leading indicators of souring at different feeding frequencies
    - Continuous
    - Feed for 8 h/d
    - Feed once daily
    - Feed every 2 days
- Organic loading
    - Every day: 7.0 g/(L-d)
    - Every 2 day: 13.9 g/(L-d)
- 18-d HRT

Long-term operations are stable at when fed daily…

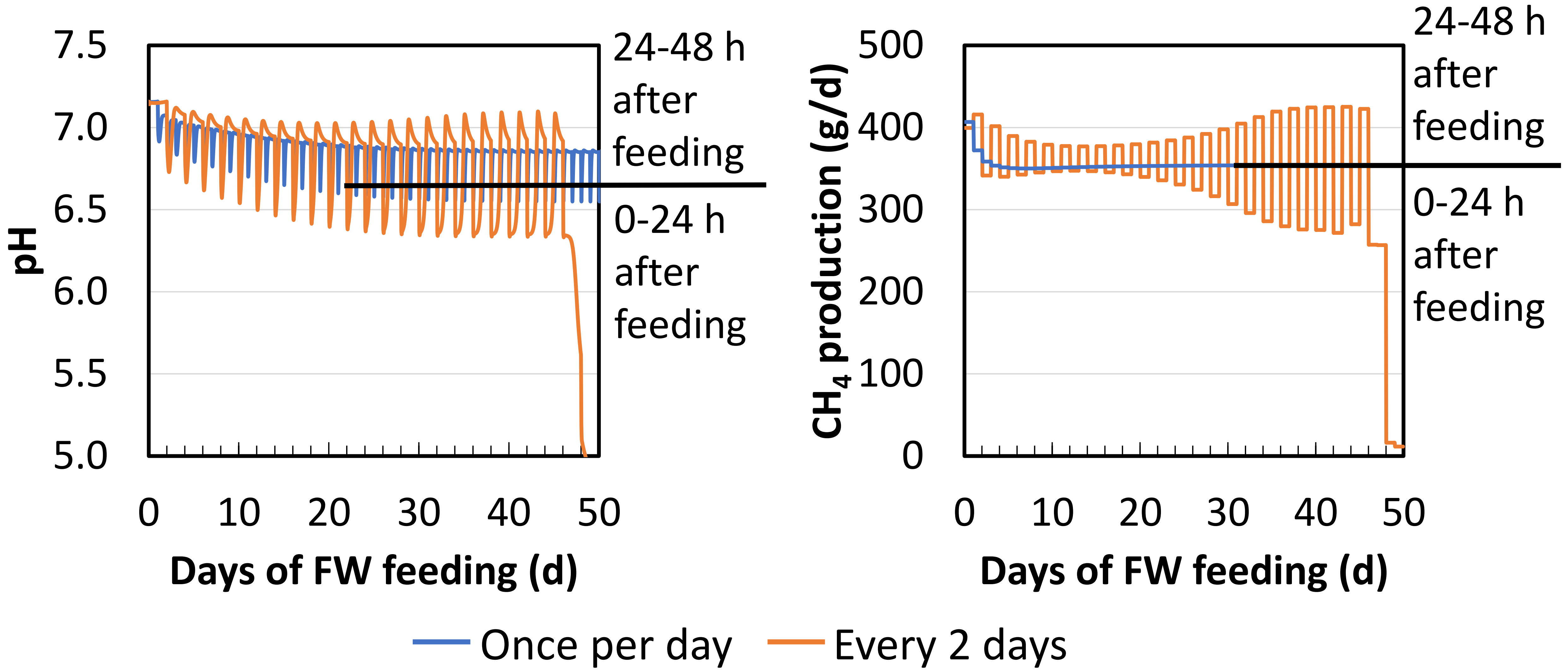


Long-term operations are stable at when fed daily but not when fed every 2 days

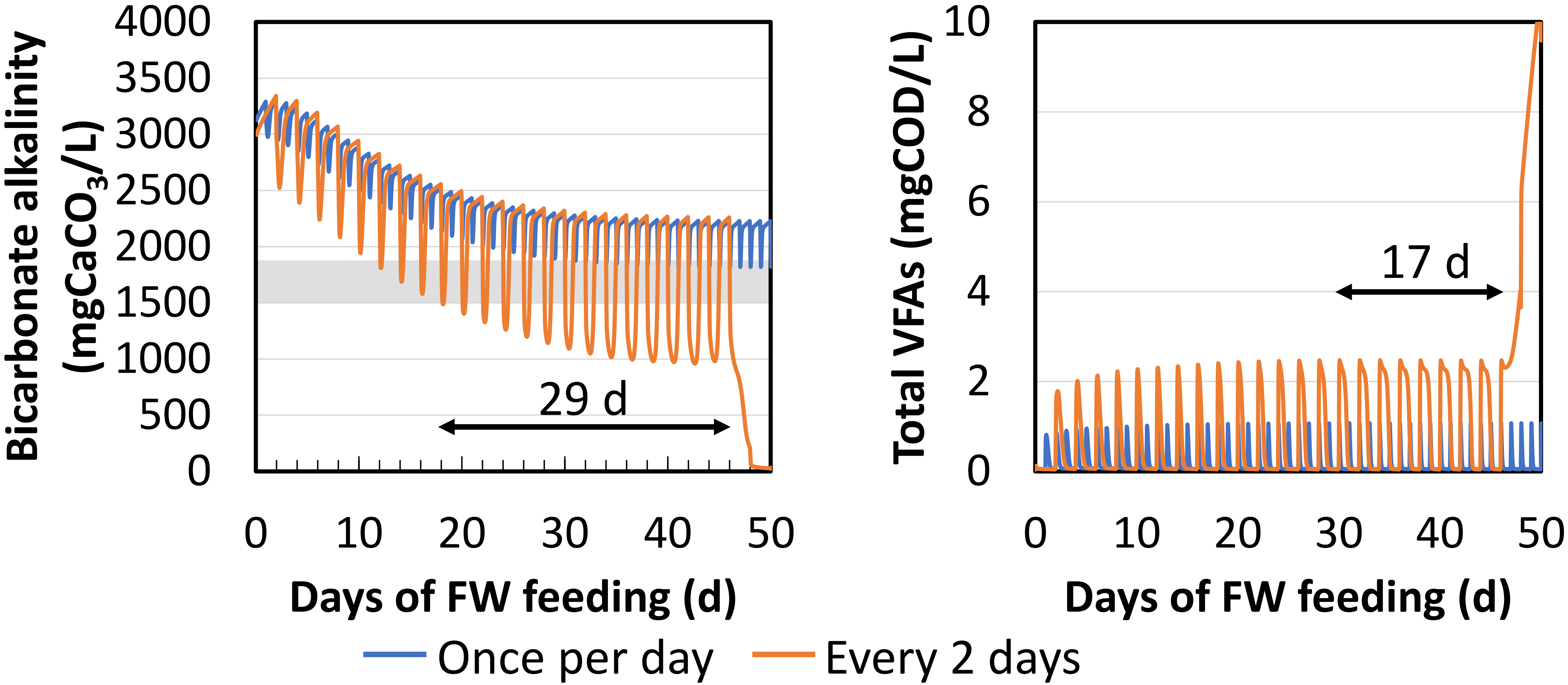




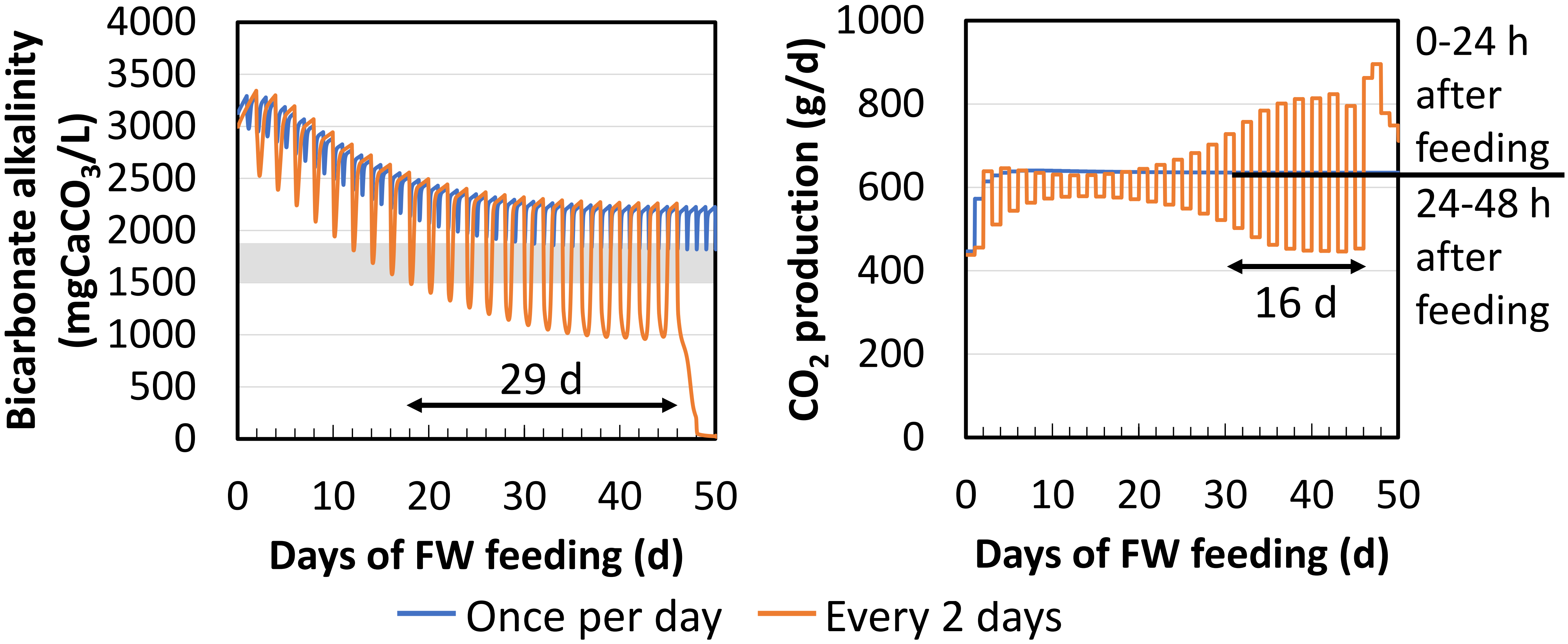
Performance is cyclical



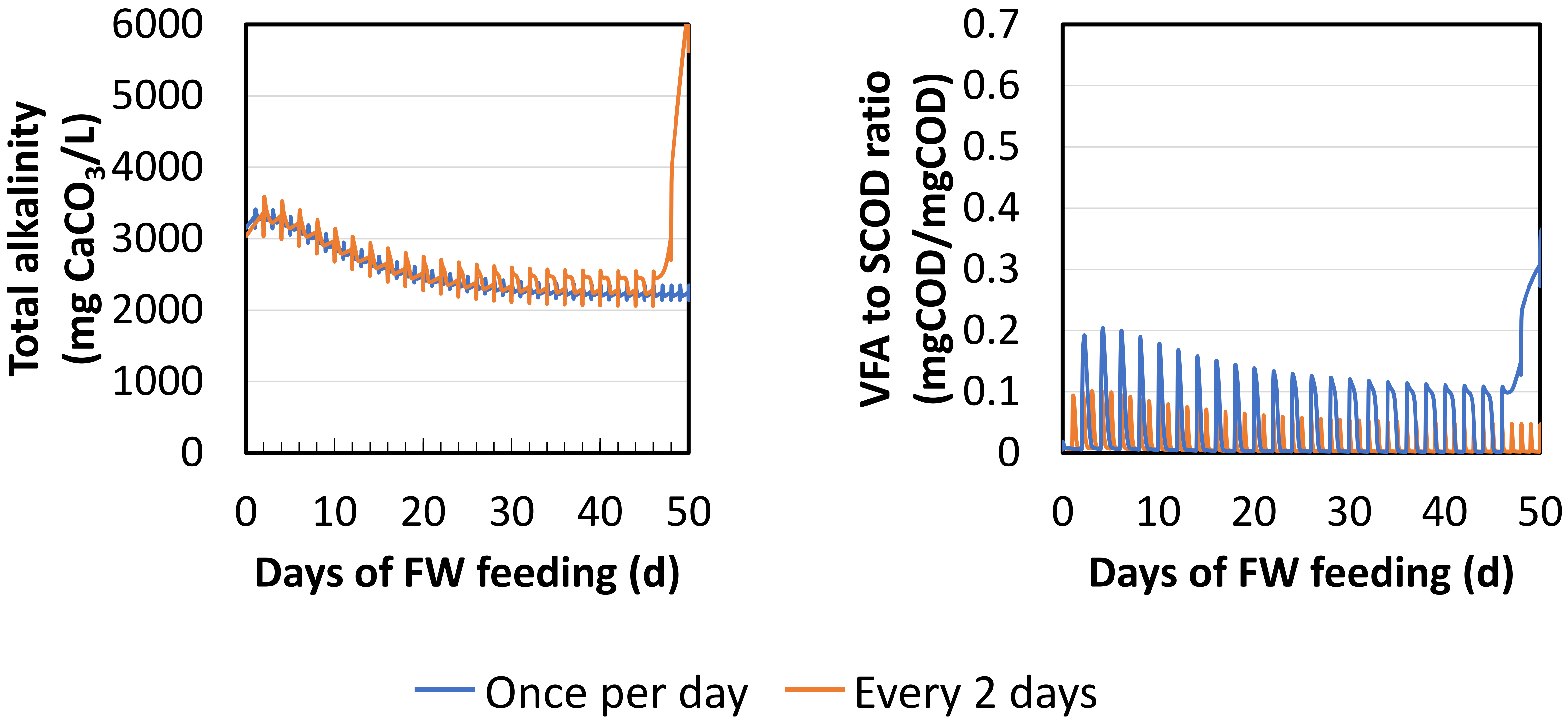
Bicarbonate alkalinity is a longer leading indicator of souring vs. VFA concentration



CO_2 off-gassing depleted the system of alkalinity, contributing to souring



Other potential indicators were lagging



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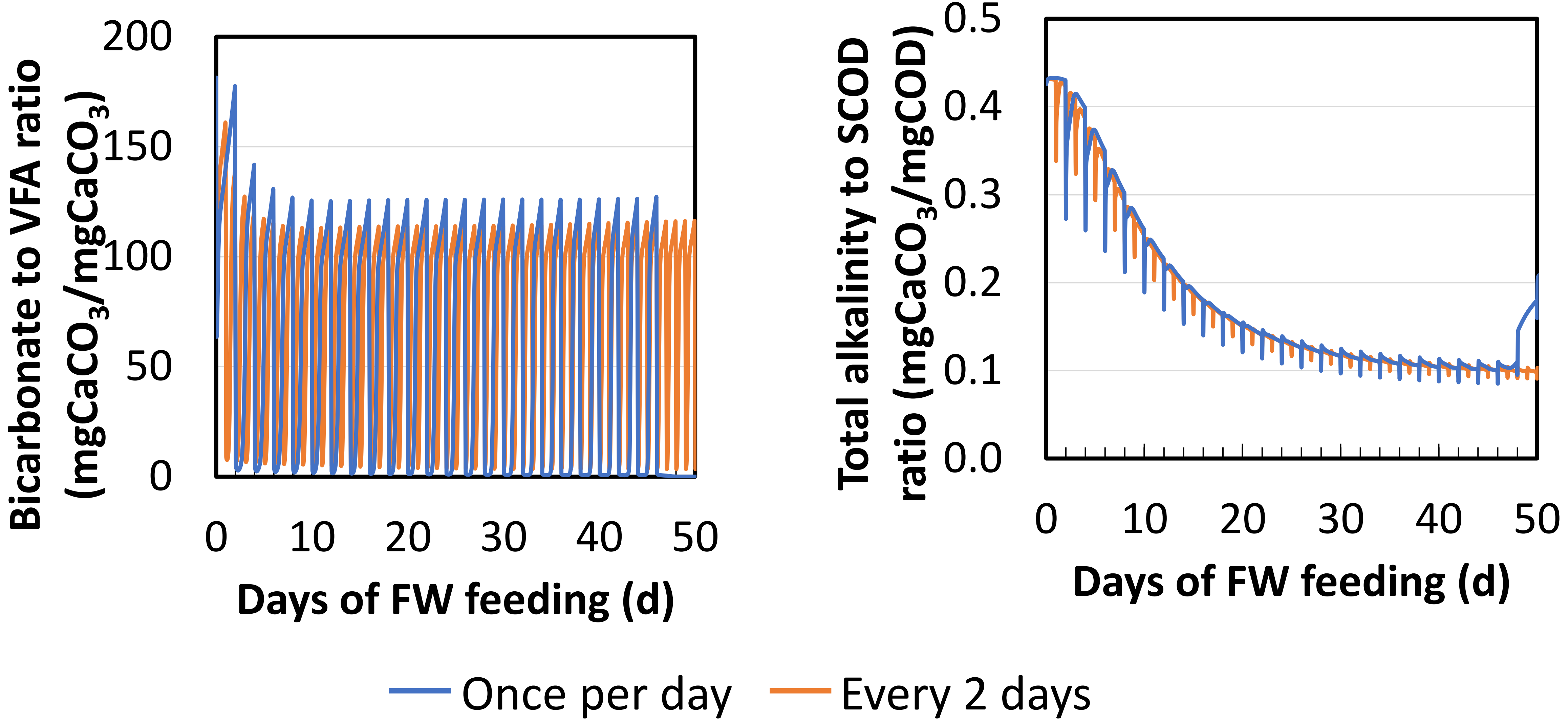

In summary

- Mathematical modeling can be used to predict souring in FW anaerobic co-digestion
- All souring was caused by a depletion of bicarbonate alkalinity
- Bicarbonate alkalinity can be monitored as the leading indicator for souring
    - Bicarbonate alkalinity = total alkalinity - VFA alkalinity

Acknowledgements

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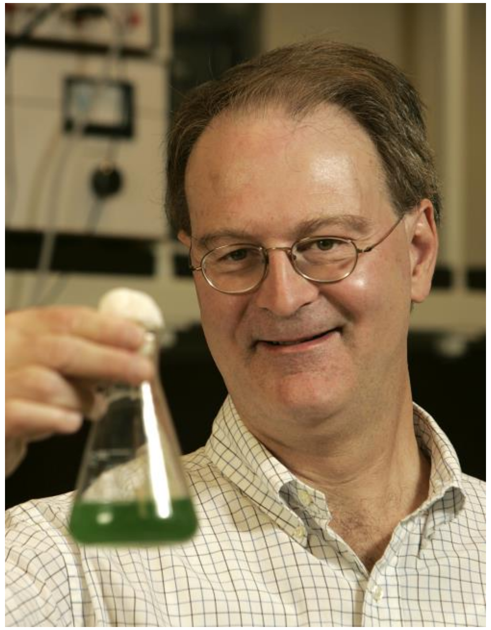

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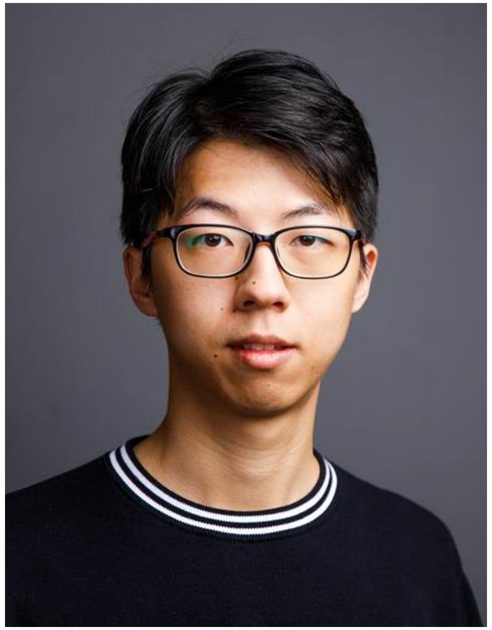

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